Isomorphic Routing Protocol

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Abstract

A mobile ad-hoc network (MANET) routing algorithm defines the path packets take to reach their destination using measurements of attributes such as adjacency and distance. Graph theory is applied to networks to form structures from patterns of nodes. Isomorphism measures equality beginning in the individual node and in sets of nodes and edges. The measurement of isomorphism is applied in this research to form paths from an aggregate set of route inputs, such as adjacency, cardinality, and network width. The path is constrained to increase in connectivity and centrality. A routing protocol is then developed that is based on the presence of isomorphism in a MANET topology. A series of simulation experiments are then conducted in the ns-3 simulator to measure the performance of the routing protocol proposed here. Finally, suggestions for future improvements are given.

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Chapter 1

Introduction

Today's information centered and dynamic world increasingly requires the representation of modern data structures with pairwise relations on a graph plane. Examples of how graph theory is shaping critical infrastructures and fields of research include its use in the mapping of the human brain [10], representing data flows or events in software [6], and now in social networking, for example in the abstraction of social groups to node clusters [27], or more broadly the categorization of interrelated information systems. A graph is a set of edges and vertices which form associations. Graph theory studies the way associations of nodes or vertices and edges form structures to define the properties of the environment they model.

A mobile ad-hoc network (MANET) can be modeled as a graph of mobile nodes and edges to represent communication. Present MANET research notes that the attributes of the node/space is random, since it lacks any constant structure and centrality. Random movement and the intermittent connections of the mobile environment expose the limitations presented by wired network routing algorithms which are used in conventional MANET protocols, such as Shortest Path First (SPF) or Spanning Tree Protocol (STP). Presently, graph theory algorithms are applied in MANET research to derive structure or determine the properties of topologies, such as bottlenecks [15] or dominating sets [15]. A gap in present research is in the application of graph theoretic measurements at the individual node association level to measure how path inputs such as node degree and concentration affect route capacity, defined as the quantity of available routes and connections, over distance. It is necessary to measure how path inputs alter or increase path duration, and the effectiveness of MANET path determination.

Graph theory can be applied to measure the presence of isomorphism, or identical node sets, in for example the one-to-many association of node degree across a path and the distance domain. Consider an example of path determination which constrains a path to traverse nodes that are maximal in adjacency to its next hop node set, increasingly from source to destination. The route capacity of such a path is maximal in quantity of adjacency to its next hop node set and is defined by the presence of successively increasing node associations. This path is increasingly isomorphic and will grow in route capacity as the requirement for connectivity with path growth increases. This example applies isomorphic node associations to an entire MANET path to greatly constrain path traversal or mitigate the phenomena that decrease path reliability.

1.1 Problem Statement

Conventional MANET protocol path measurements are often based on wired network algorithms or do not fully address the constantly changing state of MANET paths. For example, conventional MANET paths that are determined with limited knowledge of the changing topology are unquantified; a fully connected network with ten nodes presents over 180,000 possible paths, given by the following equation for n nodes:

$$(n-1)!/2$$

A MANET route is dependent on the changing orientation of the source and destination, and storage of the local topology and local traffic based maintenance [14] only does not address the continual state of topology wide route entropy, defined as the procession of a converged path to a loss state. The reduction of MANET node activity into individual measurements of isomorphism is necessary to remediate the random, variable distribution of distance and node structure of the mobile environment.

Thesis Statement:

> It is possible to increase the connectivity of MANET paths using measurement of isomorphism: in the one-to-many measurement of node degree, network width, and proximity to impending hops. Path distance in a MANET must be measured with an aggregate set of route inputs at each individual node to quantify random MANET paths and improve end-to-end delivery in mobile networks.

1.2 Summary of Results

The IRP (Isomorphic Routing Protocol) proposed here achieves end-to-end delivery in conditions which the SPF protocol, which has a much faster route computation method, is not able to deliver packets. IRP sends an average of twenty-five update messages per second while the other tested conventional MANET routing protocols, Optimized Link State Routing (OLSR), Ad-Hoc On Demand Distance Vector (AODV), and Destination Sequenced Distance Vector (DSDV) send a minimum of sixty. However, IRP uses 103,357KB/s of network bandwidth for update messages where DSDV uses 21.965KB/s. IRP delivers an average of 664 packets and the next best performance in the tested MANET routing protocols is OLSR which delivers 483 packets in the 180 second at 1m/s node speed. In another 180 second with a 4m/s node speed simulation IRP delivers an average of 494.82 packets, with SPF delivering an average of 493.76 packets, and DSDV was third in performance of the tested protocols with 66 packets delivered.

IRP's topology table is based on link state protocol and IRP exchanges the full routing table at each broadcast resulting in higher overhead. However, when IRP and OLSR are evaluated with a four second update interval IRP results in an average of 494 packets and OLSR only delivers 13.56. IRP retains routes where SPF is unable to retain them; also at 4m/s node speed SPF is able to more readily route while IRP is unable to compute a route due to node speed.

The similarity of the SPF and IRP results show that as node speed increases the capability of path determination mechanisms to keep the network converged decreases. Path wide route computation reduces path loss where SPF is unable to negotiate a path. The immediate path determination of SPF allows it to react faster at higher speeds, and IRP retains paths that SPF can not in varied instances (see Table A.2).

1.3 Contribution

This research presents a new protocol that does not depend on full periodic network convergence. Protocols like DSDV and OLSR converge periodically using broadcasts, however IRP does not fully converge at every update interval. IRP achieves distributed route computation by keeping routes directed towards increasingly connected parts of the topology. Each intermediate node routes towards the most connected point to the destination. IRP does not require a strict convergence based update mechanism to route packets effectively.

This research quantifies the routing behavior of individual autonomous nodes in MANETs. MANETs exhibit random characteristics and individual node activity [14] is the only definable property of mobility. IRP forms path measurements with individual nodes, utilizing growth in the concentration of nodes to define increasing adjacencies across path distance.

Chapter 2

Graph Theory and its Applications to MANETs, and Conventional Routing Protocol Update Methods

2.1 The Application of Graph Theory To MANET Paths

The most classical utilization of graph theory in networking has been to formally model networks mathematically, leading to routing algorithms. It is used previously to study linear and passive networks [5] and has been applied in the discipline of network theory for over 150 years [5]. Since graph theory views networks as systems of interrelations and points of interaction, in this application [5] it provides a high level analysis method that can enumerate a network without individual node level calculations [5]. The systems graph theory studies are structures derived from sets of node patterns measured independently of node quantity or topological complexity.

The implementation of graph theoretic structure to find for example the most efficient way to reach all the points in a graph is not adaptable to sets of random conditions such as those in MANETs. For example, a heuristic routing algorithm that sends route updates to all nodes using a minimal dominating set implemented in [23], reaches all nodes by forming a connection between nodes that are not reached with a conventional spanning tree [23]. However, this algorithm [23] is ineffective in a graph with one central node connected to a set of nodes which have a toroidal connection like a wheel [23]. This example demonstrates the challenge of enumerating a random network such as a MANET in such a manner. Inconstant mobility conditions expose the limitations of many path determination algorithms.

Graph theoretic patterns in networks are applied to the redistribution of bandwidth to renegotiate or "‘move"’ data according to node density [16]. The network is viewed as a cluster with "‘users"’ occupying partitions of the network that react to such interaction [16]. This type of enumeration is increasingly utilized in social networking to form associations between users and user attributes. Graph theory increases the detail that network phenomena can be observed and quantified with. It defines the individual unit of data by quantifying its place in the larger network, much as a group of user’s attributes can be collected or patterns can be formed from associations of their attributes.

Graph theory is mainly presently based on static states of network topologies. Changing networks can be optimized when their attributes can be structured to continually recalibrate, or adapt reactively, to deviations from the patterns constrained upon the measured node set. Simple evidence of such perpetual optimizations is seen in [16] which implements cliques, defined as a set of nodes which connects to the complete graph with a distance of k, termed a k-clique [24], so that the network is always in a cost efficient configuration [16]. These formations are formed independently of the configuration, in other words a "‘maximal"’ set of nodes is always present to continually accommodate an offload part of the network [16]. In this setting graph theoretic formations improve performance by up to one-quarter [16], however a MANET is a continually changing environment where nodes move over distance, limiting the reliability of topology dependent methodologies of quantifying node space.

Graph theory can be applied to MANETS to mathematically represent the formation of lines and paths [24]. Figure 2.1 below shows an example of a two-dimensional MANET topology with communication occurring between endpoints directionally:

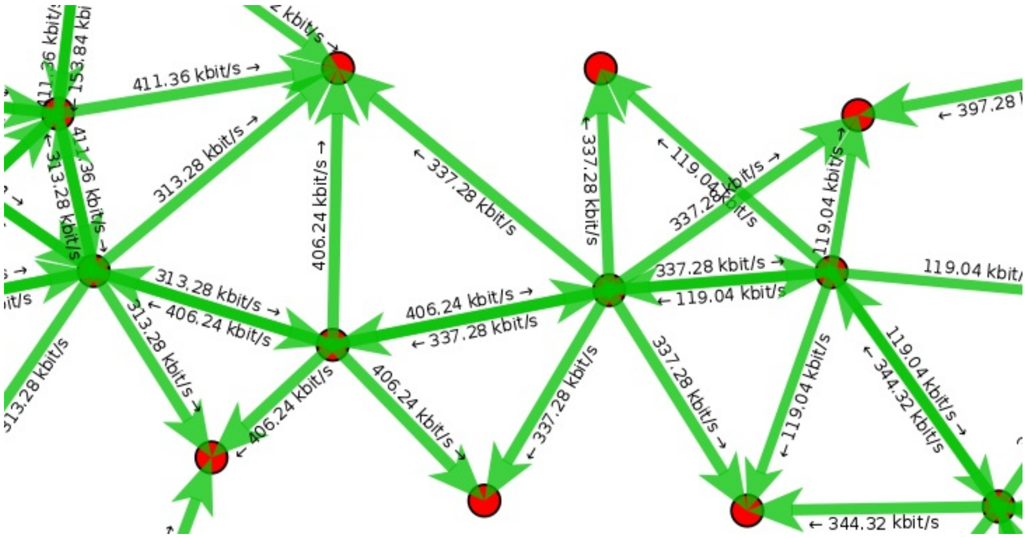

Figure 2.1: MANET with Data Transfer Between Nodes

[18]

Graph theoretic isomorphism in graph representations is identical no matter how they are arranged [24]. An isomorphic graph is defined as the propensity of the one to many connection of its members that are equally joined [24] increase in any variant of this equal connection. An increasing quantity of isomorphism in a graph increases the ordered degree sequence [3] of the path, described in variables defined in Section 3.3, and the aggregate connectivity or node capacity over distance. This research studies isomorphism over path distance and the aggregate measurement of end-to-end connections in a graph.

The measurement of topology or path wide routes relates to the study of scale free networks [28]. In [28], a large scale network is organized by selecting all nodes that make the network acyclic [28]. This acyclic graph is like a spanning tree that spans out to reach all the points in the network. This decomposition illustrates how the reduction of node space results in a set of nodes that can further measure attributes of the topology. For example, unlike a spanning tree, this acyclic graph [28] denotes the distance measurement of all subsequent points beyond the acyclic points. A stratification of network topologies with graph theory results in an increasingly concise baseline from which to reduce node space into sets of quantified autonomous node associations, just as a path is a minimal measurement of distance between two points.

The graph theory algorithm known as depth first search (DFS) [20] is an example of the minimal properties of irreducible measurements in random graphs. In [20], DFS is used to navigate a maze by proceeding to explore each cell or branch to reach the final point [20]. DFS results in the greatest performance of all the maze search algorithms [20]. [20] exemplifies how minimal graph properties are a source of efficient measurement in random graphs. The result of this implementation of DFS [20] illustrates that given a random graph, an irreducible measurement in [20] the iteration of a depth first search between two given points is the least complex and most undeviating method to form a connection. This application of graph theory to quantify the topology of a random set of paths defines a positive correlation between the individual point in a graph and the navigation or measurement of random space around it.

The growth of node associations in a randomly distributed graph is patterned after measurement of its autonomous nodes. A random graph with a small number of connections grows rapidly given a threshold value for the probability of connection between them [12], not unlike natural phenomena such as the transition of liquid water to ice [12]. When a MANET is increasingly connected, there is a greater propensity [12] for that connectivity to continue. A MANETs autonomous node members functionally determine the propensity for connections [12] between them.

This thesis constrains the measurements of connectivity in a MANET topology to a distance bound path. In [8], the term clustering coefficient refers to the number of links between a set of nodes in a graph [8]. In a MANET, a higher clustering coefficient indicates that a greater overall density of node degree is present. An objective of this research is to measure topology states like node degree and adjacency to define how node density affects the reliability of shortest paths.

2.2 Present Application of Graph Theory to MANETs

Present applications of graph theory to MANETs include Dijkstra's algorithm to derive a shortest path tree [15], and spanning tree algorithm to derive a dominating set [15], which is the set of nodes that connect all nodes in a graph [3]. These methods quantify the topology, however a challenge remains in the mitigation of random movement's effect on path reliability. Measurements of isomorphism represent the minimal measurement of changes to node associations and captures the properties of the aggregate growth of connected nodes as mobility causes the network topology to change. The benefit of individual node based algorithms that improve network performance from a centralized point is observed in [17], which utilizes a fuzzy-set approach and the Fisheye State Routing Protocol to reduce route overhead through incrementally scheduled updates according to node degree or interaction [17] at each node centrally. The many benefits of clustering [11] affirm the necessity for path wide route computation, such as how it reduces the complexity of traffic distribution [11] and establishes structure in dense networks [11]. An important benefit of isomorphic measurement based routing is that it is derived from local path inputs as well as from attributes of the greater topology.

2.3 Conventional MANET Routing Protocols

In a MANET, paths depend on successive individual node connections for increasing route capacity, defined as the presence of available connections between two end-points. End-to-end delivery in a MANET must occur without any central coordinator [14], which introduces a dependency on multi-hop routing [14] and network divisions [14]. This lack of infrastructure is the main cause of route entropy, defined as the progression of a formed route to a loss state such as a path division, and prevents the quantification of path states from node reciprocation [14] in conventional MANET settings. MANETs have no fixed infrastructure [14] from which to measure path reliability beyond individual nodes.

MANET protocol research conventionally does not measure the data used in route inputs to quantify efficient protocol performance. The characteristics for an effective MANET protocol [14] are more readily known, however conventional MANET protocols may not comply with these characteristics. For example, a MANET protocol should not rely on centralized routing [14], however there is presently no conventional protocol which can be characterized as fully distributed. The most well known protocols form routes using update mechanisms and convergence methods, such as DSDV [14] or OLSR [14], and do not utilize a distributed set of node activity. Another requirement is that MANET protocols adapt to route entropy [14], however conventional MANET protocols lack path determination mechanisms to remediate path loss and depend on update mechanisms to re-converge the network and re-establish lost routes.

MANET route maintenance conventionally defines attributes of sets of nodes to provide topology structure, and uses a method for update propagation such as broadcasting or controlled flooding. Three examples of this are: DSDV, which features a next hop dependent on a sequence number and distance measurement only [14], OLSR, which computes routes of maximal connection to a two hop node set [7], and Wireless Routing Protocol (WRP) which has increased convergence ability through a table of next hop as well as next to destination addresses [14]. These protocols commonly stratify node space, for example: DSDV uses shortest paths with the aid of updates at every topology change [14], OLSR uses a distribution of a maximal set and chooses a local two hop path and converges periodically through the exchange of topology control messages [7], and WRP's convergence method measures the proximity of the source and the destination [14]. The utility of a conventional MANET path depends on awareness of the activity in its immediate proximity, or minimally on awareness of distributed node activity (as with flooding).

Wireless network routing requires computational effort and is viewed as the bottleneck of the entire protocol stack [25]. Efficient routing requires a converged topology to route across the changing path, and route inputs (the available datum used to compute a route) affect the required computational effort and overall performance. For example, as the complexity of routing protocol roles increase, a more complex and distributed system of updates is required, as seen in the performance limitations of heavily update based protocols such as OLSR [22]. Present MANET research appears to lack an algorithm that views the path as a complete entity to mitigate the reliance on update mechanisms, sequentially increase path availability, and measure possible improvements in delivery and the utility of updates.

2.4 MANET Path Determination

The research proposed here measures isomorphic node associations in individual, autonomous [14] nodes and in the activity of an entire path. Conventional path determination quantifies a path based on incomplete measurements of external topological activity. For example, MANET path determination that is not distributed does not address path restrictions in more distant areas if path decisions are based on local path inputs. A second problem is that path determination algorithms may not differentiate between multiple shortest paths with the same end-to-end connection attributes. The cost of implementing a system such as a path determination algorithm that is based on the preemption of its intermediate systems could easily become cost ineffective and is minimally redundant [21]. Path determination efficiency is limited when distance and the distribution of autonomous nodes is measured intermittently.

The properties of MANET node activity must be defined to understand what causes MANETs to perform well. This chapter presents the concepts presently used in the analysis of MANETs. The following Chapter introduces a methodology to enumerate random node activity. An analysis of the attributes that constrain path measurement is presented to examine the transitive relationship of node interactions and adjacencies in the larger topology.

Chapter 3

A Set of Path Cosntraints to Measure Random MANET Paths

This section introduces a set of experiments that are used to quantify how conventional MANET routing protocols result in inefficient paths. The design goal of these experiments is to isolate path traversal behavior that results in the dependence of the routing protocol on route updates for end-to-end delivery. These experiments begin with the implementation of two controls. Firstly, the MANET environment, speed, mobility, and node position, is controlled so that the same conditions are tested using differing protocols. The actual test protocol path is further constrained using a path determined by a complete set of each individual node's adjacency data. The set of its attributes: in degree, network width, and cardinality to the next hop are the aggregate measurement of isomorphism in each node from source to destination.

Secondly, a control protocol is used to differentiate the experiment algorithm's path determination from that of path determination based on a strict SPF algorithm. The SPF and IRP protocols, defined in the introduction to Chapter 4 and Section 4.1 are identical in structure excepting that the SPF algorithm only measures a shortest path. The topology states during path determination that succeeds in IRP and not in SPF are recorded to define the conditions in which path traversal performance is observably increased. As a result of testing the SPF control protocol which forms near immediate routes with IRP, path divisions are traced to result from insufficient path data or path loss from movement. A MANET path is measured by the transitive relationship of path attributes at each autonomous node and the larger topology; IRP paths are are always the product of the aggregate set of isomorphism in node adjacency and subsequently the isomorphism of the entire path across distance.

3.1 A Hypothesis to Evince the Correlation Between Route Capacity and End-to-End Delivery

This thesis constrains an aggregate set of individual node measurements (route inputs) to produce route outputs that are invariable in alignment or path placement to the given set of node associations in a path. The hypothesis isolates node attributes into frequency or node density based measurements, including for example the concurrence of adjacent, same hop shortest path nodes and distance, or path growth, (route capacity) measurements such as cardinality to successive impending hops. The objective here is to test for what values are present in routes that affirm that isomorphism contributes to increased end-to-end packet delivery. An analysis of a set of values defined in Section 3.3 is presented in Section 5.1 to define path determination patterns resulting from the implementation of IRP.

3.2 Path Properties in the Mobile Environment

This section defines the properties of the transitive relationship of a path as its adjacencies increase and reduce in isomorphism with the larger topology. For example, a path may interact with a number of nodes that results in a larger set of shortest path nodes. The path either joins other adjacencies, nodes will be removed form the calculated path and no longer interact with path nodes, or become a member of the path set such that the shortest path set increases in network width at that point. As these adjacencies permute with the controlled path implemented in the experiment algorithm, the topology changes as path inputs transitively alter path space and the adjacent nodes. The resulting change in individual nodes is a path traversal transaction that is observed with the dependent variable and measured by the independent variable.

3.3 A Dependent Variable to Constrain MANET Path Determination

The dependent variable sets apart path determination from the random activity that causes route entropy, defined as the procession of a converged path to a state of path loss, in conventional MANET routing protocols. A dependent variable isolates specific behaviors of variables involved in a set of observed phenomena [4], and defines an output for all possible behaviors to prevent influence by any unaccounted conditions or inputs [4]. A MANET is quantified primarily by the centrality and autonomy [14] of its members, and the formation of a path is a measurable set of nodes within the larger topology. The experimental path is first constrained across distance (such as with the measurement of a shortest path), and secondly it is constrained in node adjacency such as in degree, proximity, and the dependent variables stated in this section. The constraints placed on mobile nodes to form an aggregate measurement of reachability in a MANET and to control the path determination process are presented in this section.

3.3.1 Shortest Path Set

The dependent variable utilizes a measurement to determine the presence of congruous shortest path nodes between source and destination. This measurement determines if a path width measurement is needed in the case that the shortest path set contains multiple nodes. The presence of shortest paths is a minimal increase in the ordered degree sequence [3] that is used to constrain a given subgraph from the larger topology and across path distance. This node set represents a proportional increase in the in-and-out degree of the path set.

3.3.2 Path Width

A measurement of network width, defined as the extent (number of hops) of lateral adjacency at a given hop, is utilized when a shortest path set is of a network width of one (two neighbors of the same hop) or greater. The MANET environment is constrained by temporary, individual node associations [14], and has no constraint or boundary [14]. Since a path requires a set of continually converged node associations, a maximal network width keeps the node activity directed towards the central point at impending hops at which path activity, such as adjacencies and route updates, occur in higher quantity. These interactions increase further along in the aggregate isomorphic path. This measurement of isomorphism in node associations is a central point in the path from which it may further propagate.

3.3.3 Node In-and-Out Degree and Spatial Proximity

A measurement of the cardinality of a node to its next hop adjacencies keeps the path's trajectory formed upon the location of increasingly distant nodes. Node in degree from the next hop and its same hop neighbors is measured to choose a path that has a higher frequency and connectivity to impending nodes. The selected path is maximal in proximity to the destination and to nodes along its path. It measures isomorphism at each hop and a maximal proximity relationship of the given path to the destination.

3.4 Deduction and Induction

This section presents the flow of logic used to design a research experiment to aggregate route inputs to measure route capacity. The effect of increased connectivity in the independent variable described in Section 3.5 is observed for increased path performance. The hypothesis results in a deduction, defined as a common behavior reduced to a specific conclusion [2], that that delivery is measurably increased. The dependent variables are values of path properties are examples of reproducible node behavior which quantify improved path determination. After correlation is determined between MANET route capacity and the end-to-end delivery of packets an induction, or the reduction of a set of measured data to a more refined conclusion [2], that paths require the presence of isomorphism in node associations is formed. It is then assumed that there is a dependency between isomorphism in a path and end-to-end delivery. After evidence is presented that route capacity measures path connectivity, and that end-to-end delivery is dependent on isomorphism then the increase of utility in MANET paths with the measurement of isomorphism affirms the hypothesis.

3.5 An Independent Variable to Measure Path Activity

The independent variables in this experiment are the rate of reception of packets per second and packet reception in IRP that was not present in the SPF control protocol. The dependent variable controls the paths used in the end-to-end delivery of packets. The dependent variable defines a varying set of conditions [2] that quantify path determination phenomena. The independent variable measures the establishment and duration of paths resulting from the dependent variable.

Chapter 4

The Isomorphic Routing Protocol

This chapter defines the protocol processes, simulation configurations, and network attributes used to measure routing performance in random MANET environment of nodes given IRP, an enhanced SPF protocol, and conventional protocols. The simulations also measure the duration of end-to-end delivery with differently configured routing protocols, movement states (or node behavior), and node speeds. The simulations in the ns-3 environment use a set of its MANET routing protocols: AODV, OLSR, and DSDV for comparison. Additionally a control module implemented in this research is implemented using SPF protocol.

Both DSDV and AODV lack path measurement mechanisms and form routes opportunistically, based on availability of routes between endpoints. The simulation scripts (which control node placement, packet delivery, and movement) are identical in these experiments to observe the performance of path determination compared to the control protocol, which is identical to IRP excepting its shortest path route computation method. One hundred different topology evaluations are performed for each protocol at two different node speed settings, one and four meters per second. Low and moderate node speed simulations are conducted in this research.

4.1 Isomorphic Routing Protocol

This section defines the structure of the Isomorphic Routing Protocol (IRP) module that is developed in C++. IRP computes its routing table by beginning with a given destination, and computes the next closest node to the source that shares the highest edge count (or in degree) with the next hop and its same hop neighbors. If there is more than one candidate, a path width computation occurs that records immediate neighbors that are on the shortest path, and if these are equal a topology width calculation occurs to determine if a greater network width is present. The computation continues until a next hop node is returned, and a route added for that node. IRP calculates a route utilizing network wide information to assure path delivery is directed to increasingly connected network areas.

IRP retains multiple equal entries until an unequal value is encountered. If more than one node has equal properties path computation is performed on the entire set at each decremented hop until an unequal value is reached or a next hop is returned. IRP assures if any hop contains a greater path measurement value that it is utilized in the path.

IRP only computes ancillary measurements of shortest path width and topology or network width if the first measurement of a node set is equal. IRP utilizes the greatest measurement of the ability of the path to reach the next hop firstly before analyzing same hop adjacencies. Similarly the shortest path set width has a higher priority than measurement of the standard network width since the shortest path set is a minimal measurement of distance. A pseudo-code representation of the IRP route computation mechanism is given below.

Algorithm 1 IRP

$i = destinationhop, i\text{-}1$
procedure ROUTECOMPUTATION(*node*)
  while $i > 1$ **do**
    $node.max(inDegree) \leftarrow nextHop.andNextHopNeighbors$
    if == **then**
      $node.max(shortestPathWidth)$
      if == **then**
        $node.max(networkWidth)$
      end if
    end if
    $i--$ ▷ Hop decrement nearer to next hop
  end while
  return *next* ▷ The next hop is returned
end procedure

IRP is based upon the Fisheye State Routing Protocol link state implementation [9]. FSR stores a set of adjacency information for each node in a topology table, with an entry for the destination IP address, neighbor set, and sequence number for each node [9]. A function to measure the hop number and in-and-out degree of each node occurs before every route computation. A variable proportional to the network width defines the number of instances of forwarding that occur. A function to calculate the shortest path and topology width is also implemented in the route table computation function.

The IRP module was coded in ns-3 using the OLSR C++ module as the base code. Since OLSR relies on timer mechanisms and link readiness measurements to maintain its topology, a method was needed to provide path maintenance for IRP. To achieve this, whenever a node receives a message from a one hop neighbor via broadcast, an entry for that neighbor is made which stores a unique integer number for that one hop neighbor. Subsequently, as neighbor nodes increase in adjacency to further distant nodes, a numerical variable is appended to each node branch originating from the one hop neighbor with the original neighbor's number as the first digit, and a number after the decimal to uniquely identify its proceeding members. As nodes combine and are increasingly combined a list of each network segment's heterogeneity is accumulated, somewhat like an expanding, overlapping tree. When a neighbor does not reply in a given broadcast cycle, its number is queried for the nodes that are included in its "‘branch,"’ and the set of neighbor losses integrated with it and not the neighbors that are still present in the network are removed.

4.2 Network Environment and Parameters

The topologies configured here test path reliability between two endpoints that are separated by eleven hops initially. The starting state of the network topologies has a forty meter vertical spacing and has thirteen rows of nodes which increase in quantity at the center of the thirteen row set, like a diamond shape. The ends are comprised of three rows of three nodes, and subsequently from four to six nodes incrementally on the top half and from four to five nodes on the bottom, with two rows of seven nodes in the center. The horizontal spacing is set to be fifty meters, and offset by twenty-five meters per row, arrayed symmetrically. The nodes are configured to start within range of their one hop neighbors and to be within reach of other nodes as node associations change. The figure 4.1 below from the ns-3 python simulation visualization tool pyviz [18] shows the topology for the experiment:

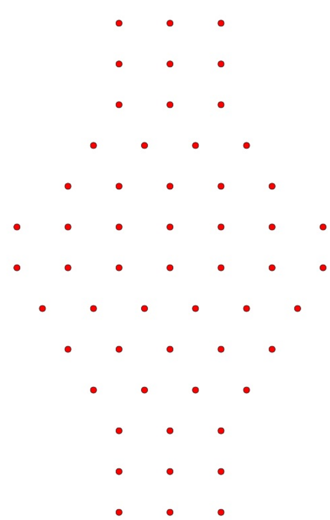

Figure 4.1: ns-3 MANET Test Topology

[18]

The simulation experiments are configured to run for a total of 200 seconds. The network converges for twenty seconds and then sends packets between a single source and destination for the remaining 180 seconds. The quantity of packets received in this sink is recorded to determine the overall performance of the tested protocols.

The MANET experiments use node speeds of one and four meters of movement per second. The mobility model implemented is the Random 2-D Walk mobility model [19], which works by going at the set speed in a random direction for a fixed amount of time, and then changing direction randomly and repeating. This duration or "‘pause"’ timer is set for three seconds in the simulations. This configuration provides a moderate level of persistent, random changes in path direction and network activity to produce consistent route entropy, defined as a degrading state of path reliability. The constant changes in node adjacencies provided by the mobility settings test the capacity of the tested protocols to retain the paths they choose, and the performance of a given update interval (route overhead and convergence).

4.3 Route Control Overhead

Route control message overhead bandwidth consumption is observed to show the rate of delivery in the presence of topology control mechanisms. The experiments are set to record every time a control message is sent out, and the size of the message. The overhead datum shows the utilization of bandwidth for control messages and routing overhead during end-to-end delivery of each protocol. The total overhead is discussed in Section 5.3. The simulations record packet delivery between the single two node packet sink to shows the effectiveness of packet delivery with existing routing protocols in comparison to IRP.

This chapter established a methodology to measure how path wide computation is tested and computed against a fast performing path determination method that only measures the shortest distance between source and destination. The tested protocols, AODV, DSDV, OLSR, SPF, and IRP each have different convergence mechanisms and either lack a path determination methodology other than availability based routing or have path determination methods of varying complexity. The following chapter presents a set of path attributes derived from autonomous nodes to exemplify the patterns of IRP's path wide route computation method. The implication of each protocol's performance on IRP's path determination is then discussed.

Chapter 5

IRP Performance

This Chapter begins with a justification of IRP by cross-analyzing a set of paths in the SPF control protocol with those of IRP. The simulation results begin with the packet reception of the two node packet sink configured to send for 180 seconds. The protocol control message overhead and message quantity with AODV, DSDV, OLSR, IRP, and SPF are then presented. Finally, a test of the Confidence Interval of the results is then presented.

5.1 Validation

The validation data is taken from simulation seven (See Table A.2) which has a packet delivery value that is 128 packets greater than SPF during the 180s delivery measurement period. The data IRP records includes the result of the search for a maximally connected hop from the destination to the source based on the out degree of each node. The shortest path width and topology width is recorded in the event that equal out degree values are present. An individual instance of the result data is comprised of the nodes selected for each hop on the way to deliver a packet from source to destination, and the dependent variable values along the path. The duration of the sample which is comprised of packets delivered in IRP and not SPF is approximately thirty seconds.

The result set is presented according to the variables and constraints that are tested in the research question. First, the hypothesis predicts that a maximal and increasing degree sequence would provide longer duration paths. This is exemplified in the result set in several ways. All of the paths have the presence of multiple two, three, four, or five out degree value nodes in a varying distribution. Every instance of delivery has at least three of these nodes, and the majority of the result set paths are comprised of five or more of these out degree values. A one out degree value node is only utilized when there is no other node available. The result set varies in the amount of hop instances that have no cardinality measurement and which have a topology width measurement as a result of the same conditions. To summarize, all of the paths utilized the out degree measurement and an out degree measurement or the path/topology width measurement for the majority of hop decisions from source to destination.

The next constraint examined by the research question is that greater network width paths contribute to overall path efficiency. Since network width is only used when there are equal out degree values, this measurement is uncommon in the result set. The shortest path width measurements are between one and four, with two adjacent nodes being the most common measurement. The majority of the network width measurements are utilized when the out degree value of a given node set is one or two, resulting in a path with a greater node density. A minimal number of the topology width entries had an equal shortest path width, which has values of either one or two. The network width measurement is an ancillary measurement intended to provide a source of potential connection when equal values exist for the out degree measurement.

The hypothesis tests for the effect of arranging random route inputs into sequentially increasing node associations. To provide internal validity in this result set, defined as the agreement of the subject phenomena to the method of examination [26], the path is constrained to adhere to the maximal value of each of the dependent variables under all conditions. The result set has a high concentration of repeat values in the range of two to five for out degree, and frequently paths which have low out degree measurements instead have multiple entries in the path for topology or shortest path width. The validity of this experiment is based on its reproducibility in all test conditions [13] since it forms results from a constant set of data in any test environment.

5.2 Packet Delivery Performance

This section presents the results of 100 simulations which show that the increase of nodal connectivity increases the overall packet delivery under conditions that SPF is not able to route. The research question this thesis seeks to answer is whether or not the presence of increasing amounts of node connections will lead to increased connectivity in MANET paths. The result data in Table A.2 repeatedly shows the ability of SPF to quickly form routes versus IRP's ability to retain paths for longer durations or more effectively.

The objective of the research question is to evaluate the results of the implementation of IRP. SPF has many instances in which it outperformed IRP and IRP also had cases with greater performance. The two protocols are identical excepting the time it takes to execute the route computation method which affects the rate of convergence and the setup time for establishing a path. SPF's route computation method is often takes less than .2 seconds compared to IRP's path determination which can take up to .8 or more and forms paths almost immediately upon receiving update information. The drawback to this is that its paths may be shorter in duration due to the lack of path measurement.

SPF forms paths more readily than IRP however IRP forms paths in many of the cases that SPF is unable to. For example in the one meter per second simulation number ninety-five in Table A.1 which shows that IRP delivered 557 packets and SPF delivered 395 packets. There are repeated instances in which IRP has a much greater delivery than SPF, such as simulation 14, 9, 42, and 48 in Table A.1. The remaining simulations from table A.1 are divided among simulation which SPF was marginally greater than IRP in packet delivery or vice-versa, or in which they were nearly equal.

The mean delivery of the one meter per second simulations show that OLSR has the best performance of the conventional protocols, shown in Table A.1. IRP and SPF perform approximately 25% better than OLSR, and have packet delivery values that are within eight packets of each other, with IRP having the greater value at 664. DSDV was tested with an eight second full route table exchange update interval, meaning that it is possible that increased performance was possible by reducing it to four seconds, which is what is used in OLSR, SPF, and IRP. Table 5.1 shows that packet delivery increases in the following order as routing mechanism changes: the lowest performance was in an on-demand protocol, AODV, then the two protocols that converge by distributing their routing table periodically, and the highest performance was in the routing protocols that broadcast their complete routing table at every update interval.

The increase of node speed to four meters per second resulted in more inconsistently distributed results. A majority of the packet delivery values between IRP and SPF in Table A.2 have a great disparity between them, with IRP either outperforming SPF or vice-versa. This clearly indicates that higher mobility either requires a readily available route or measurement based path. The tested protocols did not have a mean delivery above 66 delivered packets as shown in table 5.2. The results indicate that when node mobility causes the routing protocol become incapable of retaining routes IRP and SPF exemplify the differing path requirements of higher mobility for end-to-end delivery.

The Confidence Interval (CI) of packet delivery in the 100 simulations is measured to indicate the quality of the result predictions. The t-test is used when a sample size is small. The equation for Confidence Interval used in this research is:

$$\bar{x} \pm t(s/\sqrt{n})$$

[1]

The tables below show how much an average value from the result set will vary from the mean. A larger sample size of the number of simulations, 100, was chosen in order to have a more concise estimate.

The result values from The CI test show that there is a wider range of values in Table 5.2 for the one meter per second simulations. For example, the greatest CI occurred in AODV, with a value of 37.569, where in the 4m/s simulation in Table 5.7 the value was only 9.974. As a general rule, the fluctuation in range and the magnitude of the mean size of the packet delivery results impact the

CI. If the values were higher, then the standard deviation of the values is greater which reduced the acuity of the CI test. The result values from The CI test show that there is a wider range of values in Table 5.2 for the one meter per second simulations. For example, the greatest CI occurred in AODV, with a value of 37.569, where in the 4m/s simulation in Table 5.7 the value was only 9.974.

The AODV results indicate that the protocol influences the randomness of the data. For example, in the one meter per second tests AODV has the greatest CI at 37.569 (See Table 5.6), however in the four meter per second test has a CI of 9.974 (See Table 5.1 and 5.2). All of the tested ns-3 protocols reduce in mean packet delivery from the first test to the second however AODV reduces from 291 to 51 while DSDV and OLSR had a reduction from 367 to 66 and 483 to 13 respectively. AODV has the highest broadcast setting of all the protocols at one second which could cause a broadcast storm or cause inconsistent delivery as a result of excessive route update data and could impact the overall CI. The AODV results indicate that the protocol influences the randomness of the data. For example, in the one meter per second tests AODV has the greatest CI at 37.569 (See Table 5.6), however in the four meter per second test has a CI of 9.974 (See Table 5.2). All of the tested ns-3 protocols reduce in mean packet delivery from the first test to the second however AODV reduces from 291 to 51 while DSDV and OLSR had a reduction from 367 to 66 and 483 to 13 respectively. AODV has the highest broadcast setting of all the protocols at one second which could cause a broadcast storm or cause inconsistent delivery as a result of excessive route update data and could impact the overall CI.

The table of Confidence Interval and mean results from the tested protocols are presented below in Figures 5.1 and 5.2.

Confidence with 95% Confidence Interval with 1m/s Node Speed Simulations

Protocol	$Mean\ Packet\ Delivery \pm CI$
AODV	291.29 ± 37.569
DSDV	367.51 ± 17.080
OLSR	483.31 ± 18.383
SPF	656.45 ± 18.121
IRP	663.99 ± 15.548

Table 5.1: $Mean \pm CI for\ 1m/s\ Simulations$

Confidence with 95% Confidence Interval with 4m/s Node Speed Simulations

Protocol	$Mean\ Packet\ Delivery \pm CI$
AODV	51.09 ± 9.974
DSDV	66.01 ± 8.981
OLSR	13.36 ± 3.741
SPF	493.76 ± 28.758
IRP	494.82 ± 27.334

Table 5.2: $Mean \pm CI for\ 4m/s\ Simulations$

5.3 Control Message Overhead

This section presents the quantity of update messages and their size per second during the 200 second simulation. The results indicate that full routing table advertisement based updates are more consumptive of network bandwidth as shown in Table 5.3. IRP and SPF are set to forward the routing table a set number of times until converged, and OSLR converges every four seconds by sending TC messages [7]. DSDV periodically broadcasts its entire routing table and AODV sends hello messages every second.

IRP and SPF utilize one third of the messages per second than the other tested protocols. This indicates that despite the broadcast of the entire routing table that IRP and SPF converge rapidly compared to the other protocols. Given that the other protocols have less overall bandwidth consumption for update messages, IRP would benefit from the implementation of incremental updates to decrease the overall update size while maintaining packet delivery performance.

SPF has a lower overall update size as indicated in Table 5.3. Since IRP and SPF are identical excepting the time it takes to compute its routes, this indicates that SPF requires less time to receive an SPF message, re-compute its routing table, and forward the message to its neighbor. SPF converges faster by three messages per second consuming approximately 22,000KB per second less bandwidth for route update messages. DSDV is the most active of the protocols tested, sending either incremental or full updates at every route change. DSDV is third in bandwidth consumption and sends thirty-one times more messages than the SPF protocol and twenty-seven times more messages than IRP.

$Mean \pm CI$ **of Message Quantity and Size Per Second for 200s Simulation Duration**

Protocol	$MeanQty.Msgs/Second \pm CI$	$MeanSize(KB)Msgs./Second \pm CI$
hline AODV	67 ± 3.455	$1,340.3 \pm 75.6$
DSDV	682 ± 243.364	$21,965.4 \pm 7,797.6$
OLSR	61 ± 7.724	$11,739 \pm 1,570.5$
SPF	22 ± 5.401	$83,535.5 \pm 20,677.4$
IRP	25 ± 6.189	$103,537.8 \pm 21,642.3$

Table 5.3: Mean Message Quantity and Size Per Second for 100 Simulations

Chapter 6

Conclusion

A MANET requires a converged state to maintain routes and deliver packets like a wired network, however its node associations are completely random. Given the presence of measurable, autonomous node activity, the aggregate behavior of MANET node groups can be quantified. The distribution of this autonomy is critical to path convergence and sustained end-to-end delivery. While a MANET has random properties, it is necessary to consider methodologies to accommodate topology wide mobility.

6.1 Convergence as a Functional Requirement

The results indicate that a continually converged topology state is not mandatory to provide path determination and retain end-to-end delivery. For example, although OLSR's update interval was tested at four seconds for TC messages and two seconds for hello messages in the simulations in this research, its mean packet delivery (See Table 5.1 and 5.2) is less than that of SPF and IRP which has the same update interval. DSDV, which sends periodic full or incremental updates and broadcasts the routing table every eight seconds also had lower performance than SPF and IRP. SPF and IRP are not configured to fully converge at every update interval, instead they forward the routing table a set number of times after receiving messages from neighboring nodes.

MANET convergence is not the determining factor here for the performance of packet delivery, and is not a non-functional requirement that exclusively determines the potential for packet delivery. IRP utilizes a less converged network and less distributed updates as it only broadcasts every four seconds with four forwards and does not fully broadcast to the entire topology. Yet IRP and SPF had the highest mean packet delivery of all the protocols considered here. Convergence should not be dependent on the consumption of network bandwidth in order to have a fully distributed route computation method [14].

6.2 MANETs and Node Autonomy

Autonomous nodes are the only source of path measurement in a MANET. For example, an IRP path is a set of minimal measurements of adjacency measurements over distance constrained by the lack of isomorphism or equality in nodes it associates with. As node associations interact with the path, the connection's entropy increases. Just as multiple equal route inputs cannot be differentiated, such as when two identical paths exist, this research shows that route inputs that lack this equality cause path loss in conditions that quickly computed routes can not be retained.

6.3 Future Work

Several topics related to this research are relevant for future research into MANET protocol development. Further work to implement the reproducible instances of successful path determination decisions observed in these experiments into a more comprehensive routing framework is needed. This research defined path determination conditions that improve end-to-end delivery, however it did not completely measure the properties of random MANETs. Using the present research it is possible to study patterns in IRP routes to establish a framework for more adaptive routing mechanisms.

Implementation of this protocol alongside a more distributed MANET protocol, such as Fisheye State Routing would also present interesting results. Fisheye State Routing sends updates isomorphically, using a distribution of a timer and a one hop, two hop, and three hop neighbor set.

The incremental frequency over distance and time are proportional, and have a capacity to be measured similarly as in this research. For example, what is the effect of update delivery to increasingly distant nodes in conjunction with isomorphic path measurements? A framework could be implemented by investigating ways to improve the distribution method of updates so that they consume less overall overhead, such as a method to provide incremental route updates as opposed to a strict link state update of the entire topology table. What types of distributed methods can be determined to control message overhead and propagation to result in better end-to-end communication in a MANET?

IRP updates are larger than other protocols, and its update mechanism is still based on local broadcasts. The scope of this research is limited to controlling the path packets take to reach their destination and not the effect of forwarding mechanisms on packet delivery. Additional experimentation is needed to fully understand how random MANETs perform better through the processes they undertake when converging.

References

[1] Khan Academy. Small Sample Size and Confidence Intervals. `https://www.youtube.com/watch?v=K4KDLWENXm0`. Accessed: 2015-04-4.

[2] Oivind Andersson. *Experiment! Planning, Implementing, and Interpreting*. John Wiley and Sons, Ltd: West Sussex, 2012.

[3] V. K. Balakrishnan. *Schaums Outlines: Graph Theory*. McGraw Hill: New York, 1997.

[4] Oskar Blakstad, editor. *Experimental Research*. Explorable.com, 2013.

[5] I. Cederbaum. Some Applications of Graph Theory to Network Analysis and Synthesis. *Circuits and Systems, IEEE Transactions on*, 31(1):64–68, Jan 1984.

[6] Alexander Chatzigeorgiou, Nikolaos Tsantalis, and George Stephanides. Application of Graph Theory to OO Software Engineering. In *Proceedings - International Conference on Software Engineering*, pages 29 – 35, Shanghai, China, 2006.

[7] T. Clausen and P. Jacquet. Optimized Link State Routing Protocol (OLSR). RFC 3626 (Experimental), October 2003.

[8] L.A. Cutillo, R. Molva, and M. Onen. Analysis of Privacy in Online Social Networks from the Graph Theory Perspective. In *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, pages 1–5, Dec 2011.

[9] Mario Gerla, Xiaoyan Hong, and Guangyu Pei. draft-ietf-manet-fsr-03 - Fisheye State Routing Protocol (FSR) for Ad Hoc Networks. http://tools.ietf.org/html/draft-ietf-manet-fsr-03. Accessed: 2014-07-10.

[10] Yong He and Alan Evans. Graph Teoretical Modeling of Brain Connectivity. *Current Opinion in Neurology*, 23(4):341–350, August 2010.

[11] N. Jeyaratnarajah. Cluster-Based Networks. *Ad Hoc Networking*, pages 75–138, 2001.

[12] Haruko Kawahigashi, Y. Terashima, N. Miyauchi, and T. Nakakawaji. Modeling Ad Hoc Sensor Networks Using Random Graph Theory. In *Consumer Communications and Networking Conference, 2005. CCNC. 2005 Second IEEE*, pages 104–109, Jan 2005.

[13] Kestrel Consultants Inc. Kit Howard. Internal Validity. `http://kestrelconsultants.com/reference_files/Validating_Questionnaires.pdf`. Accessed: 2015-21-4.

[14] B. S. Manoj and C. S. Murthy. *Ad Hoc Wireless Networks: Architectures and Protocols*. Pearson Education Inc.: Upper Saddle River, 2004.

[15] Natarajan Meghanathan. *Mobile Computing Techniques in Emerging Markets: Systems, Applications and Services , Chapter 4: Applications of Graph Theory Algorithms in Mobile Ad hoc Nnetworks*. IGI Global, Hershey, PA, USA, 2012.

[16] Wei Ni, I. Collings, J. Lipman, Xin Wang, Meixia Tao, and M. Abolhasan. Graph Theory and its Applications to Future Network Planning: Software-Defined Online Small Cell Management. *Wireless Communications, IEEE*, 22(1):52–60, February 2015.

[17] S. Nithya Rekha and C. Chandrasekar. A Fuzzy Set Approach in MANET with FSR (Fisheye State Routing) Protocol. *International Journal of Scientific Engineering Research*, 3(10):1–6, October 2012.

[18] ns3. ns-3 Discrete Event Simulator. `https://www.nsnam.org/`. Accessed: 2015-04-4.

[19] ns3. Random Walk 2d Mobility Model. `https://www.nsnam.org/doxygen/random-walk-2d-mobility-model_8h.html`. Accessed: 2015-04-4.

[20] A.M.J. Sadik, M.A. Dhali, H.M.A.B. Farid, T.U. Rashid, and A. Syeed. A Comprehensive and Comparative Study of Maze-Solving Techniques by Implementing Graph Theory. In *Artificial Intelligence and Computational Intelligence (AICI), 2010 International Conference on*, volume 1, pages 52–56, Oct 2010.

[21] J. H. Saltzer, D. P. Reed, and D. D. Clark. End-to-end Arguments in System Design. *ACM Trans. Comput. Syst.*, 2(4):277–288, November 1984.

[22] T. Sanguankotchakorn and T. Sangsrichun. OLSR Control Overhead Reduction by Using Game Theory. In *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2011 8th International Conference on*, pages 373–376, May 2011.

[23] M. Sengoku, H. Tamura, K. Mase, and S. Shinodu. A Routing Problem on Ad-Hoc Networks and Graph Theory. In *Communication Technology Proceedings, 2000. WCC - ICCT 2000. International Conference on*, volume 2, pages 1710–1713 vol.2, 2000.

[24] M. van Steen. *Graph Theory and Complex Networks*. Martin Van Steen: Lexington, 2010.

[25] J.A. Stine. Cross-Layer Design of MANETs: The Only Option. In *Military Communications Conference, 2006. MILCOM 2006. IEEE*, pages 1–7, Oct 2006.

[26] Vik Wadhwani. Internal Validity. `http://www.indiana.edu/~p1013447/dictionary/int_val.htm`. Accessed: 2015-21-4.

[27] Yuhao Yang, Chao Lan, Xiaoli Li, Bo Luo, and Jun Huan. Automatic Social Circle Detection Using Multi-View Clustering. In *Proceedings of the 23rd ACM International Conference on Conference on Information and Knowledge Management*, CIKM '14, pages 1019–1028, New York, NY, USA, 2014. ACM.

[28] Bing Yao, Xia Liu, Wan-Jia Zhang, Xiang-En Chen, Xiao min Zhang, Ming Yao, and Zheng-Xue Zhao. Applying Graph Theory to the Internet of Things. In *High Performance Computing and Communications 2013 IEEE International Conference on Embedded and Ubiquitous Computing (HPCC/EUC), 2013 IEEE 10th International Conference on*, pages 2354–2361, Nov 2013.

Appendix A

Appendix

Packet Delivery with 1m/s Node Speed for 180s Duration and 100 Simulations

Simulation	AODV	DSDV	OLSR	SPF	IRP
1	515	415	621	715	697
2	299	451	554	691	713
3	269	392	501	695	659
4	414	453	542	699	709
5	420	403	331	713	686
6	357	385	534	679	712
7	494	458	464	681	659
8	397	475	592	703	709
9	128	406	406	534	689
10	399	316	543	713	714
11	172	390	398	655	704
12	361	375	497	712	665
13	471	340	541	712	606
14	414	440	449	568	708

15	605	493	504	672	562
16	387	150	492	677	713
17	401	376	533	628	659
18	568	262	531	714	715
19	15	481	378	589	482
20	255	350	495	603	696
21	560	422	413	710	714
22	259	322	534	716	654
23	684	462	332	710	715
24	632	227	581	718	677
25	686	312	609	702	675
26	517	361	472	636	688
27	328	245	365	651	665
28	561	386	620	612	700
29	352	552	605	717	717
30	442	387	547	674	694
31	154	440	495	715	716
32	193	472	401	682	635
33	90	229	602	713	667
34	184	450	274	649	710
35	223	453	474	710	621
36	81	421	492	696	700
37	7	273	244	277	340
38	152	358	559	698	714
39	29	280	590	649	603
40	66	465	356	716	710

41	157	528	527	567	582
42	196	430	545	620	702
43	163	280	552	666	708
44	193	300	525	714	663
45	306	377	415	698	685
46	226	375	572	713	712
47	99	342	464	612	690
48	4	358	479	650	712
49	130	225	450	661	709
50	193	451	475	705	614
51	216	328	506	691	602
52	669	443	536	705	680
53	226	366	487	716	702
54	674	519	534	707	667
55	553	387	439	647	617
56	408	323	511	716	709
57	279	364	579	645	657
58	609	266	648	718	716
59	562	433	431	686	655
60	550	338	384	716	717
61	94	90	541	715	710
62	309	494	587	712	636
63	89	321	282	320	297
64	59	384	376	574	488
65	338	327	375	615	708
66	44	342	502	715	713

67	30	534	493	711	706
68	0	392	569	700	678
69	274	356	556	715	712
70	137	532	504	713	708
71	181	245	599	715	710
72	390	317	459	554	569
73	291	355	453	712	708
74	459	421	427	715	707
75	574	320	519	711	703
76	128	419	539	717	715
77	551	464	512	708	712
78	0	203	510	615	697
79	526	325	556	571	701
80	300	326	539	703	711
81	284	443	627	644	647
82	91	337	538	589	715
83	31	381	462	714	712
84	184	347	502	718	716
85	86	287	449	652	706
86	163	172	552	710	626
87	72	389	423	691	715
88	187	427	536	666	696
89	0	342	534	359	635
90	165	338	471	709	688
91	305	379	539	698	682
92	481	363	307	599	574

93	378	306	584	715	719
94	350	306	234	648	559
95	124	457	282	395	557
96	405	292	424	714	709
97	196	298	246	439	583
98	294	299	327	321	344
99	410	285	435	561	640
100	195	375	431	635	616

Table A.1: Simulated Packet Delivery at 1m/s Node Speed and 180s Duration

Packet Delivery with 4m/s Node Speed for 180s Duration and 100 Simulations

Simulation	AODV	DSDV	OLSR	SPF	IRP
1	8	127	27	624	583
2	21	31	21	609	633
3	101	40	12	594	583
4	20	84	4	581	580
5	88	42	0	655	681
6	143	122	58	621	668
7	101	87	20	313	441
8	90	13	40	686	650
9	47	112	0	291	381
10	21	135	0	430	494
11	49	118	9	500	538
12	0	19	0	608	264
13	19	88	3	457	449
14	2	116	0	381	355

15	43	38	0	193	336
16	66	39	32	316	488
17	74	39	31	622	619
18	15	43	19	473	544
19	8	24	14	485	416
20	73	80	6	387	502
21	137	118	19	635	646
22	66	78	19	654	630
23	52	48	5	479	461
24	99	191	18	576	445
25	14	149	5	642	622
26	31	37	0	277	410
27	269	183	68	636	640
28	16	85	0	660	586
29	30	92	20	513	646
30	14	2	9	479	395
31	45	51	20	674	678
32	10	49	2	406	441
33	64	109	15	653	611
34	6	85	6	472	538
35	113	33	7	363	380
36	37	18	2	415	487
37	5	0	0	171	156
38	114	85	18	509	567
39	9	33	2	387	253
40	35	57	14	596	556

41	50	122	24	547	644
42	62	38	0	379	372
43	56	150	47	477	486
44	45	36	1	267	288
45	3	50	13	626	636
46	48	51	28	524	541
47	0	103	26	516	558
48	27	88	13	697	631
49	19	17	22	265	242
50	30	62	0	499	411
51	23	74	11	374	417
52	10	49	0	476	515
53	117	61	18	607	585
54	111	149	33	548	547
55	184	114	15	433	569
56	30	10	1	635	682
57	24	65	27	528	499
58	133	49	6	635	642
59	11	6	0	457	505
60	35	79	1	574	587
61	84	169	138	648	531
62	40	39	10	501	533
63	24	27	14	199	215
64	48	57	0	381	417
65	65	91	0	552	566
66	65	127	21	536	486

67	34	15	0	389	455
68	46	88	0	665	594
69	5	65	0	632	563
70	209	72	2	496	428
71	50	16	39	649	695
72	52	70	3	598	635
73	59	57	17	636	566
74	57	63	21	467	506
75	14	26	0	555	566
76	44	48	3	457	491
77	33	12	6	385	431
78	2	0	0	256	305
79	125	164	21	551	517
80	64	68	5	551	306
81	12	81	3	455	540
82	68	23	0	636	658
83	29	94	43	648	550
84	59	64	19	634	608
85	63	109	31	578	612
86	116	170	39	668	582
87	12	76	10	509	502
88	83	22	3	485	604
89	22	4	33	168	251
90	4	57	0	625	646
91	0	10	0	418	405
92	8	84	11	718	275

93	119	69	0	584	578
94	16	7	2	444	491
95	7	34	0	166	134
96	16	47	0	524	585
97	89	33	3	221	313
98	0	0	0	59	30
99	19	16	8	296	296
100	74	54	0	349	306

Table A.2: Simulated Packet Delivery at 4m/s Node Speed and 180s Duration